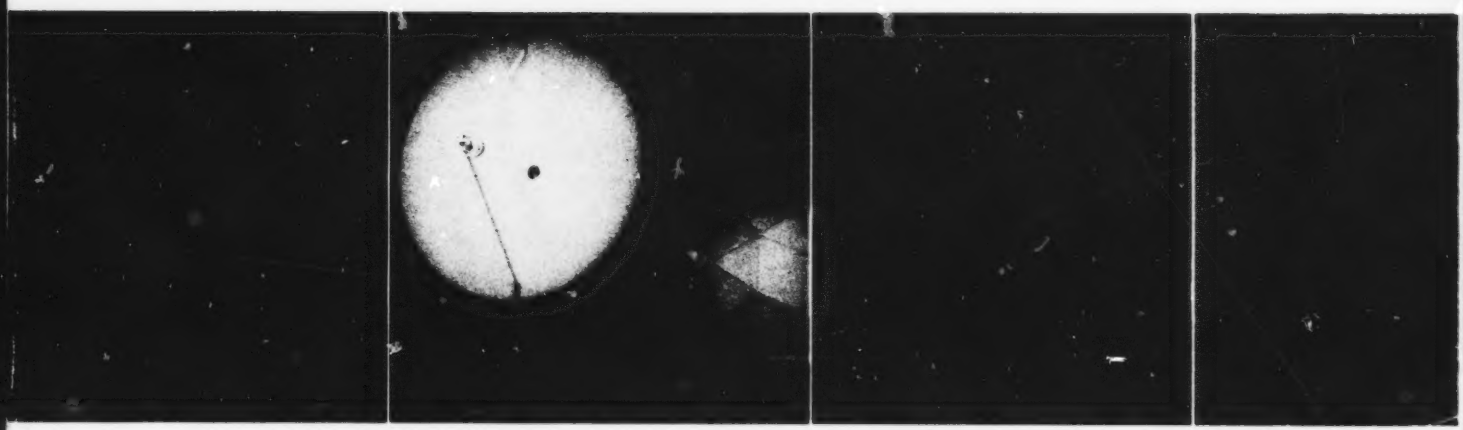
Research and operations 1980 - 1985

Weather modification in Alberta

Summary report and recommendations



ALBERTA RESEARCH COUNCIL

Natural Resources Division
Atmospheric Sciences Department

87-00976/

Research and operations 1980 - 1985

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October 1986

Cover photograph left to right

A severe hailstorm that occurred in Alberta on August 11, 1972.

Radar systems at the Red Deer Airport used for weather research (large antenna), cloud seeding control (dome-covered radar), and aircraft tracking (flat antenna).

Research aircraft used for studying hailstorms. On the left is the Cessna Conquest turboprop aircraft developed by INTERA and the Research Council. This aircraft, equipped with state-of-the-art laser sensors, measures properties of clouds before and after seeding. These are recorded and analyzed by an onboard computer system. On the right is an armour-plated T-28 aircraft from the South Dakota School of Mines and Technology. This aircraft measures conditions in the heart of the storm.

A promising wheat crop near Delburne, destroyed by hail on August 11, 1982.

ALBERTA
RESEARCH
COUNCIL

October 1, 1986

Honorable Peter Elzinga, Minister of Agriculture
Honorable Shirley Cripps, Associate Minister of Agriculture
Legislature Building
Edmonton, Alberta
T5K 2B6

Dear Ministers:

I have the honor to transmit, herewith, the Summary Report and Recommendations of the Alberta Research Council on the Research and Operations of the 1980 to 1985 Weather Modification Program. A forthcoming report, comprising technical papers, will provide the detailed scientific results of the program from which this report is derived.

Respectfully yours,

R.W. Stewart
President
Alberta Research Council

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Preface

The Alberta Research Council conducted a research and operational weather modification program in central Alberta during the period 1980-1985 inclusive. The year 1980 was a transition year in which the Alberta Research Council assumed management of the weather modification project. The current five-year experimental program started in 1981. Hail suppression through cloud seeding has been the focal point of this program, with exploratory studies of cloud seeding to increase rain and snow.

The cost of the five-year program was $22,730,000 —of which $17,420,000 was contributed by Alberta Agriculture and $5,320,000 by the Alberta Research Council.

This document constitutes the summary report of, and recommendations for, the program. It contains a brief history of weather modification activities in Alberta, the rationale for, and objectives of, the 1980 to 1985 program and the conclusions and recommendations. A brief summary of applications of technology developed for weather modification research to non-weather-modification problems is also included.

The research results are presented in greater detail in an accompanying report, which consists primarily of technical papers. Analysis of the data obtained during the last five years is far from complete. New results will be forthcoming within the next year which will lead to more definitive conclusions.

Acknowledgments

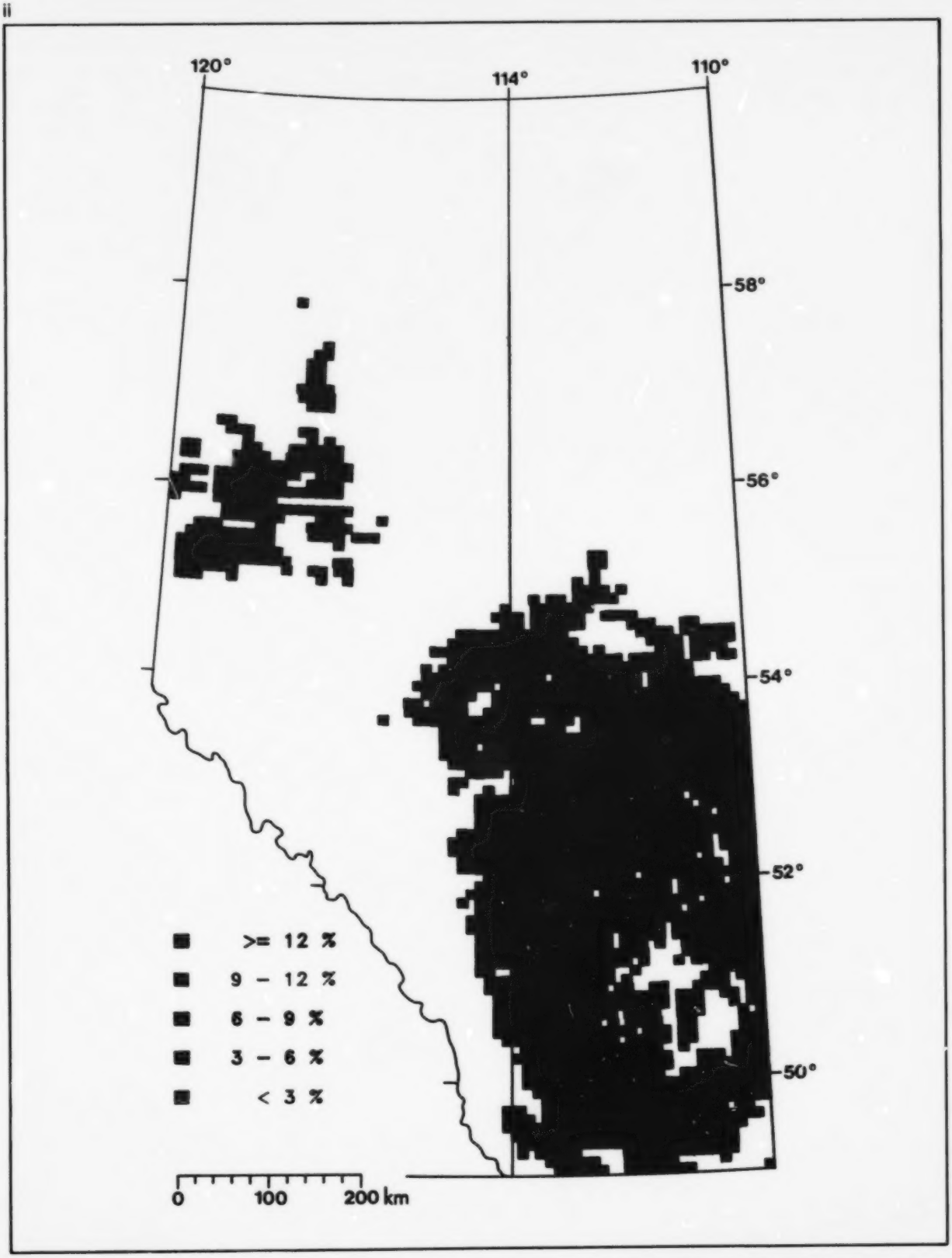
This past five year weather modification research program was a major undertaking that has gained enormously by the participation of many people and organizations. The inspiration and support of Drs. G. Goyer and B. Barge in the program's early stages are acknowledged. The Alberta Research Council has benefited from and appreciates the sage advice, patience and encouragement provided by the Advisory Committee on Weather Modification under the chairmanship of Mr. J. Christie. The financial support of Alberta Agriculture is most gratefully acknowledged with special recognition to Dr. A. Olson for his effective liaison between Alberta Agriculture and the Alberta Research Council.

The interaction with our colleagues at the Atmospheric Environment Service, and various universities and research agencies in Canada and around the world is acknowledged and appreciated. In particular, the guidance provided by Dr. P. Smith of the South Dakota School of Mines and Technology, during his sabbatical at the Alberta Research Council was most helpful.

The Technical Review Committee of Chairman Dr. R.F. Reinking, U.S. Dept. of Commerce, Mr. S.A. Changnon, Illinois State Water Survey, Dr. H-R. Cho, University of Toronto, Dr. J.A. Flueck, University of Colorado, Dr. G.B. Foote, U.S. National Center for Atmospheric Research, Mr. T.J. Henderson, Atmospherics Inc. Fresno, CA and Dr. G.A. Isaac, Atmospheric Environment Service, Toronto, who met at the Research Council in late 1985, are acknowledged with thanks for their many helpful suggestions concerning the analysis of the research results and ideas regarding future weather modification research.

The valuable economic study referred to in this report, carried out by Dr. C. Ross and by P. Woloshyn of the Economic Services Division of Alberta Agriculture, is also acknowledged.

Lastly, a most sincere acknowledgment to the farmers of Alberta who contributed so greatly to the success of the program with their unceasing support, particularly in taking rain and hail measurements and answering untold numbers of telephone inquiries regarding hailstorms and crop damage.



The average annual loss-to-risk ratio by township based on records of the Alberta Hail and Crop Insurance Corporation. The red and black squares indicate townships with average lossos exceeding 9 and 12% respectively. Blank spaces indicate areas with less than 20 years of insurance data.

Executive summary

The importance of agriculture to the Alberta economy and the heavy costs associated with hail damage and drought have focused attention on the use of weather modification techniques. Because agriculture contributes $3 billion to the provincial economy, adverse weather can be devastating. For example, during the period 1980 to 1985, average annual hail damage cost about $150 million. In addition, the 1985 drought cost farmers an estimated $650 million. The most common type of weather modification is cloud seeding, which involves injecting clouds with dry ice or silver iodide. Results of the last five years of research in the province lead to optimism about the use of cloud seeding to decrease hail and to increase rain and snow.

Research results

A better understanding of the physical processes that produce hail has been gained by investigating the whole precipitation process right from the large-scale synoptic weather patterns associated with fronts and low pressure systems to the microscale precipitation processes that occur within a cloud. The current state of knowledge about the Alberta hailstorm has been demonstrated to be essentially correct.

Results from hailstorm seeding experiments indicate that cloud seeding can increase the number of potential hail embryos or (in some storms) can cause potential hail embryos to precipitate prematurely. Evidence has been found that there are more hailstones on the ground from operationally seeded storms, but more observations would be required to determine if the size of the hailstones is significantly changed.

Because of limitations in the measuring and observing facilities, research has not yet demonstrated that more hail embryos lead to smaller hailstones or that fewer embryos result in less hail on the ground.

Computer calculations suggest that cloud seeding decreases hail (by nine percent) and increases rain (by seven percent). Research based on analysis of crop damage suggests a decrease in the loss-to-risk ratio of about 20 percent. However, this decrease, or parts of it, could be due to other factors such as climate change or insurance practices rather than to cloud seeding.

These results give reason to be optimistic about suppressing hail in the most common types of storms.

Research also indicates that towering cumulus clouds can be made to rain by seeding, even when such clouds would not rain naturally. This is significant since towering cumulus clouds are just as prevalent in drought periods as they are in periods of normal rainfall.

Limited observations of snow clouds over the Rocky Mountains in southern Alberta imply that a potential exists for increasing mountain snowpack.

Based on a 20-year operating period, the capital and operating costs of a cloud seeding program in Alberta would be recovered if annual crop losses were reduced by about five percent. Given experimental evidence to date, this is a realistic goal. Rain and hail experiments could be easily combined, as aircraft, radar, weather office assistance and other observational support are the same for both.

Recommendations

Of the three forms of weather modification considered, that is hail suppression, rain augmentation and snow increase, the hail problem is the most complex and difficult to solve, but substantial progress has been made and hail suppression looks feasible at least for some types of storms. It is recommended that hail suppression research receive continued support to address the questions that remain. It is also recommended that continued analysis of the data obtained from the 1980 to 1985 program be supported to provide more definitive conclusions about the effectiveness of weather modification and to help focus future research efforts. Further experimentation is required and recommended to optimize the seeding technology. In particular, seeding delivery techniques should be examined to improve coverage of storms.

Alberta support is recommended for an international project called Hailswath II. Participants from the United States and Europe would gather in Alberta in 1988, bringing their equipment, to carry out an intensive hailstorm study to address some of the questions that still remain.

Due to the success of the rain augmentation project, it is recommended that the rain research program be expanded.

Funding is also recommended for the SNOWATER project, proposed to adapt snow augmentation technology for use in Alberta.

Operational cloud seeding should be carried out by the private sector. However, every effort should be made to evaluate its effectiveness and a strong link should be maintained between the research and operational components of future weather modification programs.

Additional benefits

Weather modification research results in the development of a broad range of expertise and supporting technology which can be applied to other areas of government and private enterprise. The meteorological expertise associated with the weather modification evaluations has been applied to crop yield modelling for Alberta Energy and Natural Resources and in oil production studies for the Alberta Oil Sands Technology and Research Authority (AOSTRA). Some of the computer programs have been used by Syncrude in environmental work.

A research aircraft developed jointly by INTERA Technologies and the Alberta Research Council has been used in air pollution studies for Alberta Environment in addition to weather modification research. INTERA has also been successfully marketing the technology and experience gained from its involvement with the weather modification project in the international marketplace. They now have a three-year, $10

million weather modification contract with the Greek government. Data collected by the aircraft during the weather modification program will be used by American researchers in a study aimed at revising icing standards for commercial aircraft.

The radar data collected as part of the weather modification program have been analyzed for Alberta Environment to assist in assessment of severe weather events and applied to the development of forecasts of damaging lightning for the Canadian Electrical Association. Radar data are also being used by Alberta Government Telephones to study signal fading during heavy rainfall. These contracts indicate that other Alberta agencies are developing a reliance on the weather radar system that supports weather modification research.

These examples demonstrate how the offshoots of research into weather modification help keep Alberta in the forefront of technology in many related fields.

Conclusion

The potential economic gains to agriculture from cloud seeding are substantial. Furthermore, the Alberta Research Council has developed a world-class team of scientists, and advanced technologies with potential applications in many areas of industry. Therefore, it is recommended that weather modification receive continued support.

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Introduction

The potential of weather modification

The success of Alberta's $3 billion agricultural industry depends largely on the weather. Drought, hail, frost, floods and tornadoes cost Albertans hundreds of millions of dollars annually.

During the period 1980 to 1985, hailstorms caused an average $150 million annually in direct losses to crops. Secondary economic losses could add another $50 million to this amount. On the rare occasions when a severe hailstorm passes over a large city, the losses can be even more dramatic. A hailstorm that hit Calgary on July 28, 1981, caused an estimated $125 million damage and a hailstorm that passed over Munich, Germany on July 12, 1984 is thought to have caused one billion dollars damage.

Lost agricultural production due to insufficient moisture is also estimated at $150 million per year. The severe drought of 1985 is considered to have cost Alberta farmers $650 million.

The devastating effects of hail and the lack of adequate water supplies have focused attention on the use of weather modification techniques to alleviate the problem. Weather modification potentially has a very favorable cost-benefit ratio. A five percent reduction in annual crop losses would be required to recover the capital and operating costs of a cloud seeding program.

The history of weather modification in Alberta

Crop losses due to hail damage in the early 1950s prompted farmers in the area north and east of Calgary to form the Alberta Weather Modification Co-operative and hire I.P. Krick and Associates to carry out a commercial hail suppression program.

In 1956, a project was initiated by the Alberta Research Council to study Alberta hailstorms in order to design and test means for suppressing hail. Participants in this early project included the Atmospheric Environment Service of Environment Canada, the National Research Council and the Stormy Weather Group at McGill University. This phase of research continued until 1968. During these early years, fundamental information was collected on the characteristics of hail in Alberta such as its frequency at particular locations, the size of hailstones, the size and duration of hailstorms, and the weather patterns associated with hailstorms.

By 1969, it was believed the understanding of Alberta hailstorms was sufficient to begin a series of airborne cloud seeding experiments called Project Hailstop. By 1973, a seeding technology had been developed whereby silver iodide flares were dropped into the tops of clouds developing on the edges of hailstorms.

The provincial government created the Alberta Weather Modification Board (under the Department of Agriculture) in 1973 to direct weather modification research and operations. The major emphasis of the research was a randomized seeding test. Using observations obtained by interviewing farmers about the time, location and nature of hailfall, and those obtained from weather radar, a statistical comparison of data from seeded and nonseeded storm days was conducted. Results were inconclusive because none of the various measurements of hailfall were accurate enough to reliably detect a seeding effect over the short time period of the project.

In 1980, after an interim year, the Alberta Research

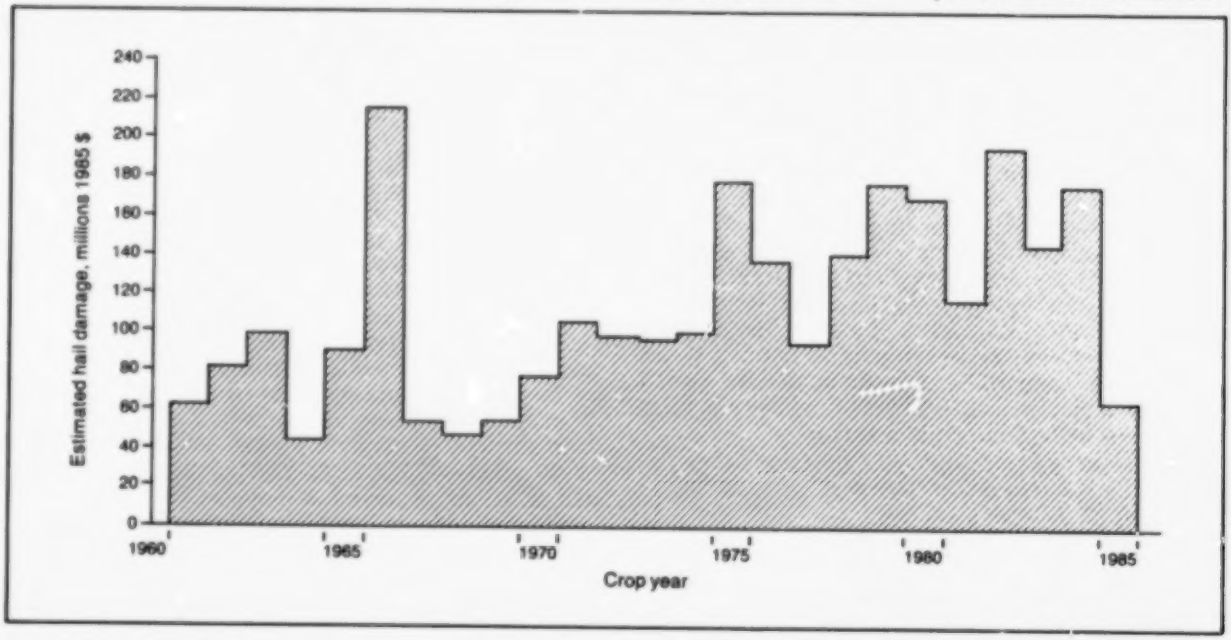

Figure 1. Estimated total annual crop damage in Alberta due to hail (expressed in 1985 dollars).

Council assumed full responsibility for research and operations in weather modification. An Advisory Committee on Weather Modification was formed by Alberta Agriculture to provide the Alberta Research Council with guidance on the general direction of the program from the point of view of the farm community. Up to this point the program had dealt exclusively with hail suppression, but it was now expanded to include rain and snow increase studies.

Objectives for the period 1980-1985

During the period 1980 to 1985, the weather modification program emphasized a better understanding of the physical processes occurring in storms and the effects of cloud seeding upon them. This seemed essential to evaluate seeding effects reliably in a relatively short time period and to develop optimum seeding techniques. The overall goal of the program was to gain enough information to assess the feasibility of conducting, at a later date, a definitive cost-benefit analysis of weather modification in Alberta. Although the primary emphasis was on hail suppression, secondary objectives were rain increase and snowpack augmentation.

To understand the physical processes that produce hail, it is necessary to investigate the whole precipitation process right from the large-scale synoptic weather patterns associated with fronts and low pressure systems to the microscale precipitation processes that occur within a cloud. Hailstorms vary considerably in intensity, size and duration. These variations are now known to be determined by the environment in which the storm occurs and, for the most part, by processes that begin several hours before the storm forms. This investigation required a considerable amount of advanced technology.

The overall goal of the program incorporated five specific objectives:

1. To assess whether cloud seeding sufficiently influences hailstorms to cause a substantial change in hailfall. To meet this objective an aircraft equipped with cloud physics instrumentation, a weather radar facility and an upper air observing system were used. The aircraft facility was developed jointly by INTERA Technologies and the Alberta Research Council. In preparation for a future economic evaluation of cloud seeding for hail suppression, forecasting techniques were improved to provide methods to predict storm behavior, help detect seeding effects and improve cloud seeding operations. New observational techniques were investigated to provide measurements of hailfall that could be used to evaluate cloud seeding.
2. To assess the potential for increasing rainfall by seeding cumulus clouds. For this, the same aircraft and radar facilities were used.
3. To investigate the potential for increasing snowfall in the Alberta Rocky Mountains by cloud seeding. The aircraft facility was also used for this.
4. To investigate optimum seeding techniques for various types of weather modification, using two seeding materials (silver iodide and dry ice); as well as three delivery methods (seeding at cloud top; seeding at cloud base with aircraft; and seeding with ground-based generators). In particular, the ability of ground-based generators to inject suitable amounts of seeding material into clouds was evaluated.
5. To routinely seed hailstorms using aircraft.

Operational cloud seeding

During the program from 1980 to 1985, hailstorms were routinely seeded by aircraft from June 20 to August 31 in the region from Calgary to Red Deer, carrying on the earlier seeding program of the Alberta Weather Modification Board. Seeding was also conducted north of Red Deer until 1981. Seeding aircraft and operations staff were under contract to INTERA Technologies of Calgary. Six seeding aircraft were used in 1980 and 1981 with five from 1982 to 1985, including a special "research seeder" for the rain and hail seeding experiments. Each aircraft was equipped with flares and acetone solution generators for seeding. Aircraft were directed to the storms from the radar control site at the Red Deer airport.

Cloud seeding techniques

Since the discovery of silver iodide as an ice forming (nucleating) material in 1946, a number of cloud seeding techniques have been developed to generate the seeding material and dispense it into the clouds. Usually, the microscopic particles are generated by burning silver iodide rods in an electric arc, burning silver iodide and acetone solution or by burning silver iodide in a pyrotechnic mixture in flares or rockets. Rockets containing a silver iodide charge are used extensively in the Soviet Union, and a number of its satellite countries, and in China for hail suppression seeding. Most other countries are using, or have used, ground-based generators or flares carried by aircraft to deliver seeding materials to clouds.

Cloud-top seeding

Cloud-top seeding involves the discharge of small pyrotechnic flares, carried under the belly of the aircraft, into the tops of developing cloud towers (feeder clouds). Flares are dropped one km apart as the seeding aircraft flies over the cloud towers. The aircraft returns within a few minutes to make another pass.

The cloud-top seeding delivery system was developed in Alberta in the early 1970s based on studies of the structure and behavior of Alberta hailstorms. The initial technique was modified twice to reflect changes in aircraft (from a jet to piston engined aircraft), and again due to improved understanding of the hail formation process in the storm. The technique is now being used on hail projects in other countries.

Because of timing and placement accuracy, this technique has generally been the preferred seeding method. Still, the actual seeding coverage achieved can vary from a high of near 75 percent for some storms to a low of near zero.

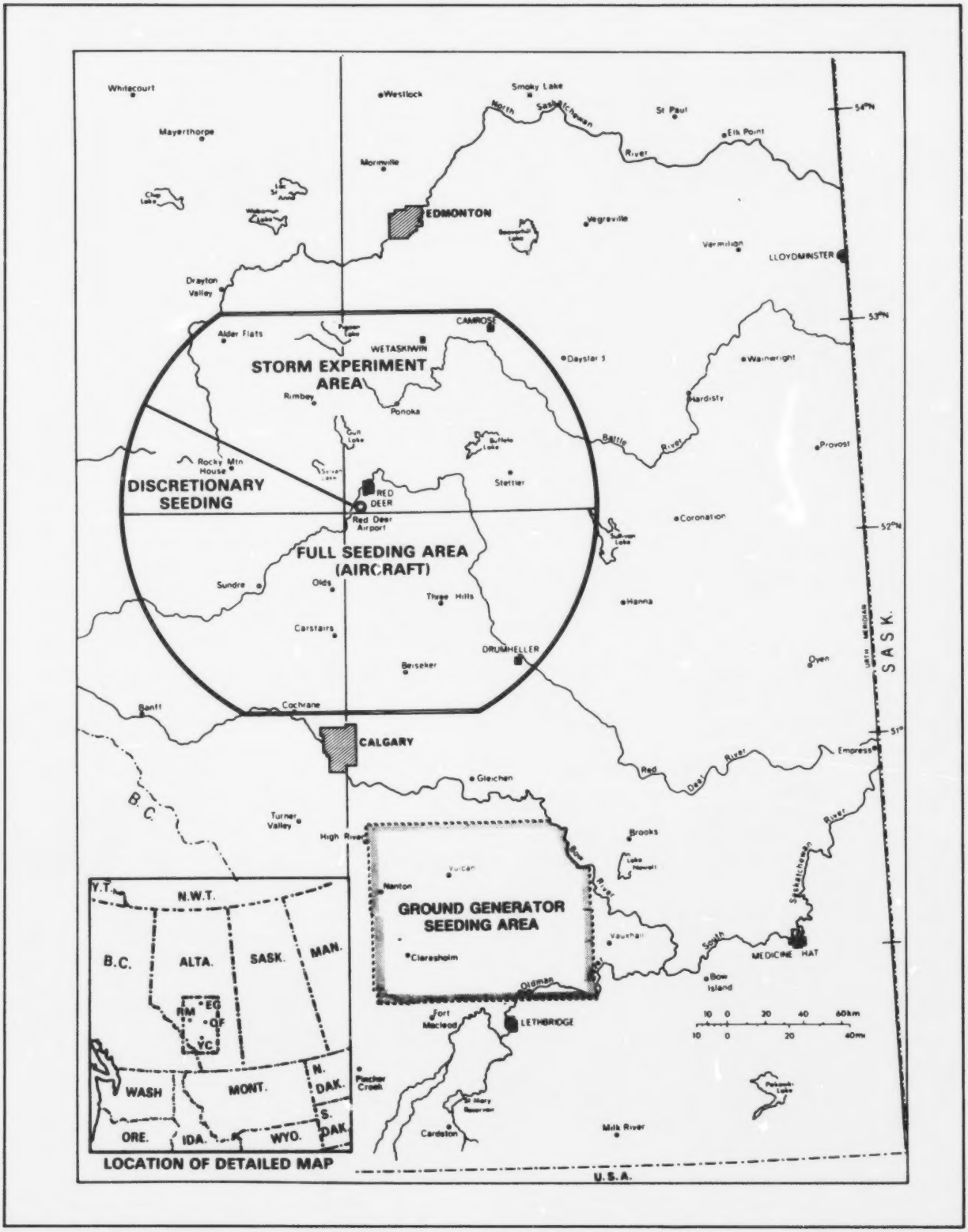

Figure 2. Weather Modification Program experimental areas. The circular area between Edmonton and Calgary was the principal target zone of the Alberta Hail Project. All hailstorms that occurred in the southern half of this area were routinely seeded for hail suppression. Storms that occurred in the northern half were used for research. The area south of Calgary was the ground-based seeding target area.

Cloud-base seeding
Cloud-base seeding uses flares or generators attached to the aircraft which burn silver iodide in acetone. The aircraft circles or flies below the cloud in the updraft area feeding it and the updraft carries the seeding material to the upper parts of the storm.

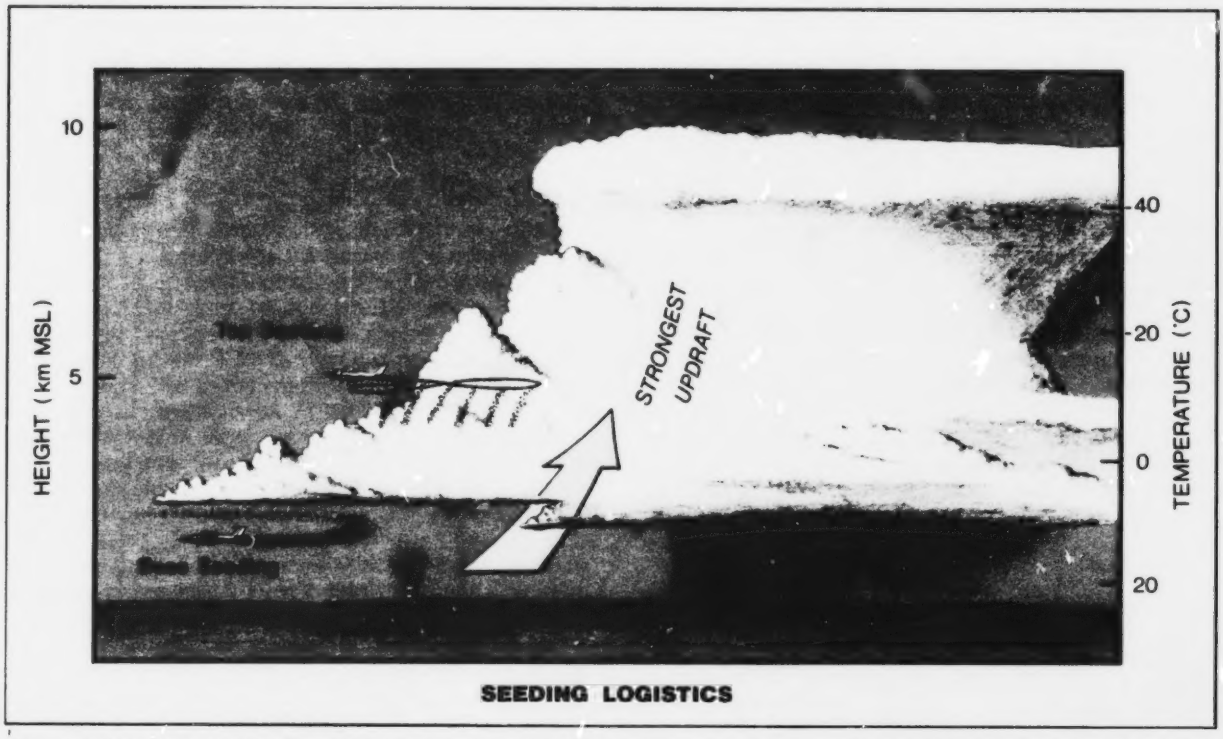

Figure 3. Side view of a hailstorm indicating the cloud seeding methods used in Alberta. For cloud-top seeding, aircraft fly near the top of the target cloud releasing either silver iodide flares or for some research experiments, dry ice pellets. The flares burn as they fall through the cloud releasing billions of ice nuclei in the form of smoke particles. This produces a curtain of seeding material. In cloud-base seeding, aircraft fly just below the base of the clouds releasing silver iodide smoke that is carried into the cloud by its updraft. The seeding material is produced by flares burning on the aircraft wings, or by smoke generators attached under the aircraft. Ground-based seeding uses a network of generators and relies upon natural air currents to carry the ice nuclei to the clouds.

Hail

Alberta hailstorms

Investigations of the storm environment have shown that even though the various weather systems are vastly different in size (from single clouds to large frontal systems), they are intricately linked in a chain of events that ultimately leads to hail on the ground. Thus, in order to formulate a complete hailstorm model, the various links needed to be isolated and understood. This new appreciation of the effects of large weather systems on the development of hailstorms has resulted in improved forecasts of storms and a potentially useful tool for the evaluation of cloud seeding effects.

Hail occurs in central Alberta (within a 130 km radius of Red Deer) on an average of 61 days during the summer. The majority of hailstorms (85 percent) occur between noon and 11:00 pm with 90 percent of hailswaths less than 30 km in length covering less than 200 sq. km. However, hailswaths can be over 300 km in length and 30 km in width from storms lasting for three or four hours. Hailstorms normally develop along the foothills during the afternoon, then move eastward over the farmlands and can continue producing hail into Saskatchewan.

Hailstorms result from energy imbalances in the atmosphere—imbalances that produce storms generating power equivalent to the electricity used by a city the size of Edmonton or Calgary in a year. Large-scale weather systems such as low pressure areas and fronts generate up to a thousand times as much energy as a hailstorm. These atmospheric forces are linked to hailfall by a complex chain of processes. Satellite imagery shows a clear tendency for convective clouds to develop within a framework of larger

cloud complexes which in turn are associated with parent weather systems. These large systems influence the atmosphere on a regional scale, producing conditions favorable for the formation of hailstorms many hours before the actual storm develops.

Current theory suggests that these events, in conjunction with the influence the mountains have on the airflow and with solar heating, focus cloud development along the foothills. Airflow from over the mountains creates a "lid" that in the early stages suppresses cloud development. However, at the same time, the "lid" increases the potential instability of the atmosphere so that when it finally erodes, intense air currents capable of supporting large hailstones occur. The storms then move off the foothills depositing their hail load.

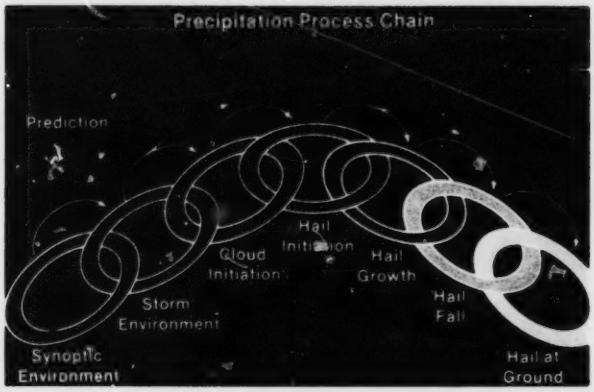

Figure 4. The "precipitation process chain" illustrating the sequence of weather events leading to hail. The synoptic weather determines the storm environment which in turn determines cloud development. The cloud development determines if or when hail growth starts, how fast it will be and how long it will continue. These factors determine the number and size of hailstones that fall to the ground.

Most hailstorms in Alberta have a series of smaller clouds upwind of the main storm. The exact location of these clouds appears to depend upon the available moisture and winds in the environment. These clouds form at regular intervals in the same location relative to the storm and their formation appears to be determined by the interaction between the storm's downdraft (produced by rain and hail falling out of the cloud), its inflow (produced by warm air rising ahead of the storm) and the environmental winds. Because these clouds move towards and merge with the main storm, they are called feeder clouds. The growth of hailstones appears to start in these feeder clouds.

The growth of a hailstone

The growth of a hailstone occurs in two stages. The beginning stage, called embryo formation, must occur

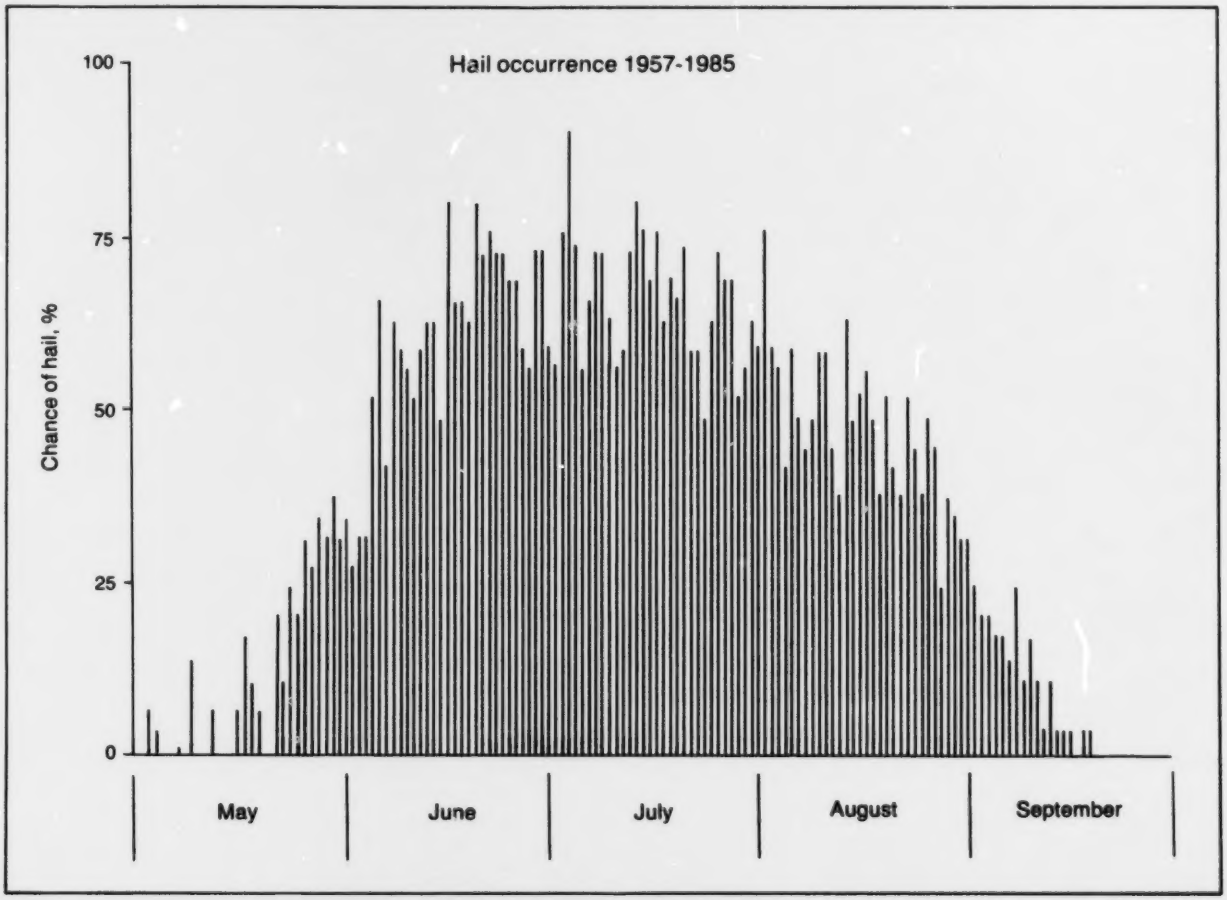

Figure 5. The climatological chance of hail occurring somewhere in central Alberta on any given date during the summer.

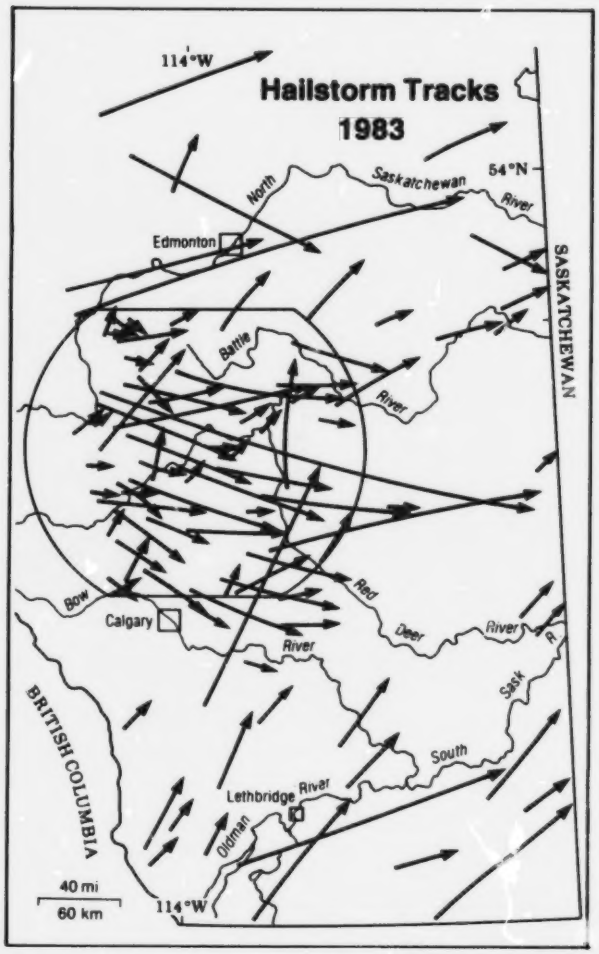

Figure 6. Hailstorm tracks during 1983. The arrows indicate the center line of the storms.

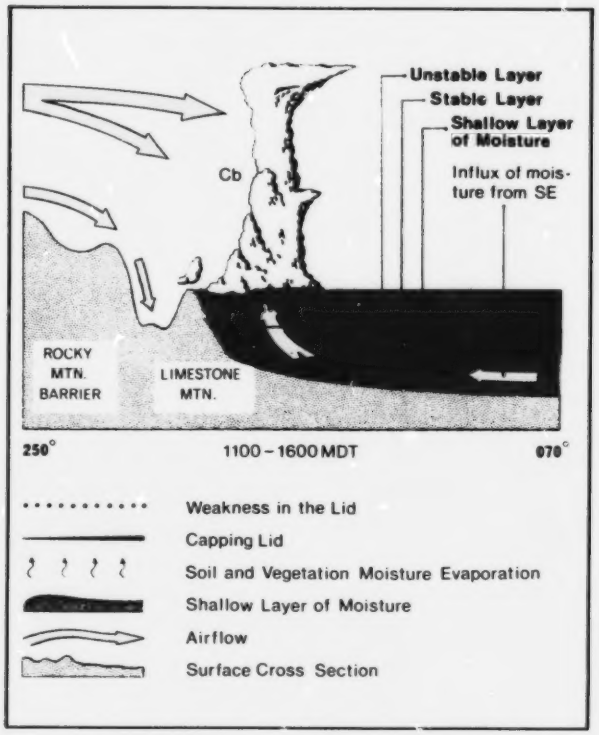

Figure 7. A schematic illustration of the effects of air flow from large weather systems crossing the mountains and the reverse air flow towards the mountains at lower levels creating a 'convective lid'. Daytime heating at the ground and approaching cooler air from the Pacific erodes the lid permitting storms to develop.

in small or young clouds with weak updrafts such as feeder clouds. The final growth to a hailstone, though, must occur in a strong and moist updraft such as in the main storm.

All clouds contain millions of water droplets. These water droplets will remain unfrozen (supercooled) even at temperature as cold as −40°C if no ice nucleating particles are present. Most natural ice nucleating particles in clouds are dust which are effective only at temperatures of −15°C and colder. Therefore, once cloud tops are colder than −15°C, ice crystals develop. These ice crystals grow by colliding with and collecting water droplets and smaller ice crystals in the cloud. Although water droplets also grow, ice crystals can grow much faster in Alberta clouds. Once an ice particle has reached a size of 1 mm, it is a potential hail embryo.

For a hailstone to form, a hail embryo must be caught and carried up by a strong and moist updraft that will keep it hovering aloft long enough to collect and freeze thousands of water droplets and ice crystals. This happens when the feeder cloud, in which the embryos develop, merges with the main storm. When the hailstone grows too heavy to be held aloft by the updraft it falls to the ground.

Hail suppression concepts

Modern hail suppression efforts do not attempt to control the storm itself, but seek to modify only the hail growth process within it. Most hail suppression theories involving cloud seeding are based on what is known as the "beneficial competition" or "competing embryo" hypothesis. This concept assumes that the amount of supercooled water in the hail cloud is the limiting factor on the mass of hail produced. Introducing enough artificial hail embryos can reduce the sizes of the hailstones reaching the ground by forcing natural hailstones to share the available liquid water with artificial ones. Smaller hailstones melt more readily so that the total hail mass at the ground is less, reducing damage to crops. Artificial embryos are produced by seeding clouds with materials that produce additional ice nuclei.

This has been the rationale behind the seeding operations and experiments in Alberta since the early 1970s. However, beneficial competition involves the risk of increasing the natural hailfall without ameliorating its effects if the natural embryos do not consume all the available liquid water or if too few artificial embryos are added.

More recently, an additional hail suppression concept, known as "premature rain out", has been proposed by Soviet and other scientists. This concept rests on the fact that ice nucleating materials such as silver iodide can initiate ice crystals at warmer

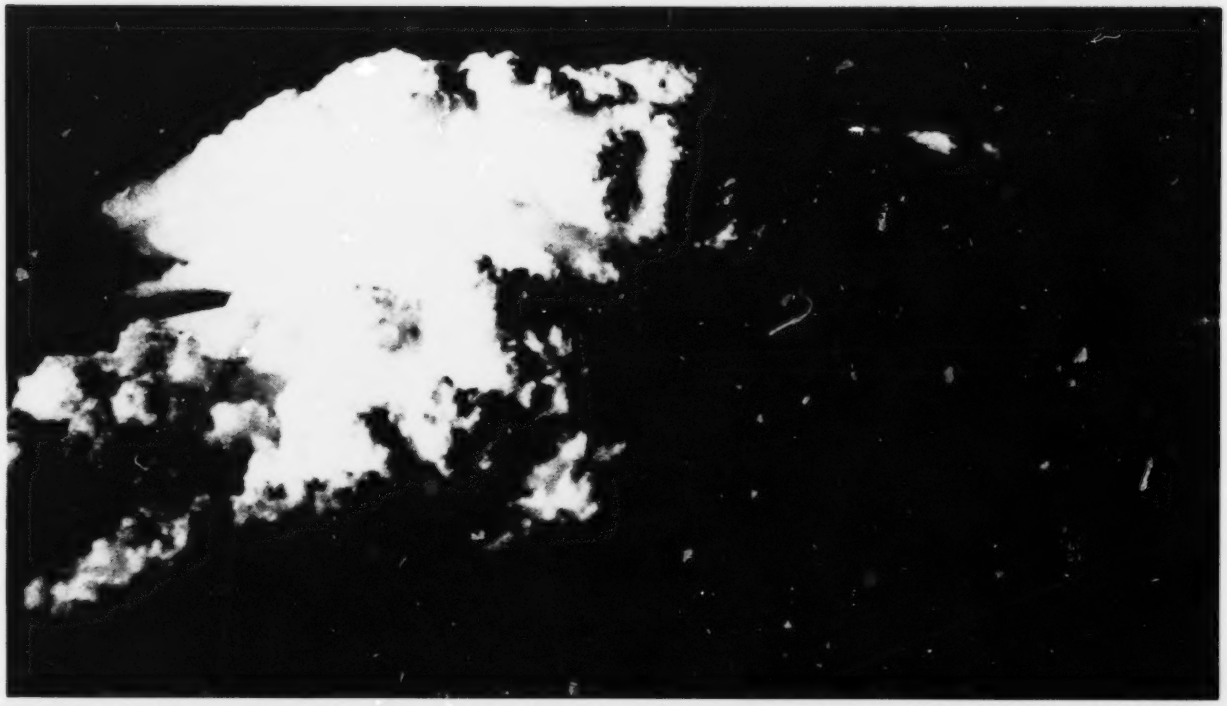

Figure 8. An aerial view of a hailstorm. Warm moist air flowing from the lower left of the photo, rises to form feeder clouds (near the left center of the photo) where moderate updrafts support the growth of hail embryos. The feeder clouds later merge with the main storm which has a strong updraft in which the embryos grow to large hailstones.

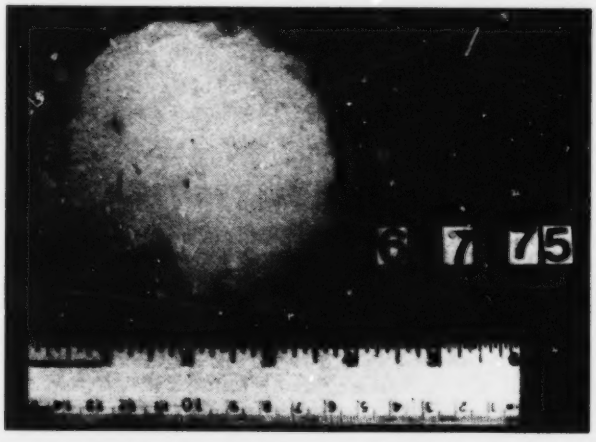

Figure 9(a). The largest hailstone on record in Alberta fell near Wetaskiwin on July 6, 1975. With a diameter of 10 cm and weighing 249 g, it fell at 150 km/h.

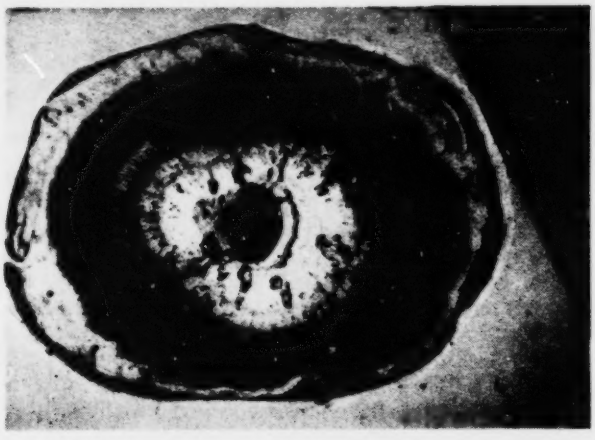

Figure 9(b). A thin slice through the center of a hailstone which fell in central Alberta on July 21, 1982. This hailstone grew from a 4 mm conical ice pellet. The alternating layers of clear and opaque ice of the hailstone indicate that this stone either passed through a series of different growth environments or grew in conditions that fluctuated with time. Studies of such thin slices of hailstones provide detailed information on how hailstones grow.

temperatures than normal, close to 0°C, and therefore earlier in the lifetime of the cloud. This should start the precipitation process in the feeder clouds earlier and result in potential hail embryos falling out of the feeder cloud before it merges with the main storm so that fewer embryos are delivered to the updraft in the main storm.

Testing the concepts

Because both concepts—the beneficial competition and the premature rain out—involve changing the number of embryos in feeder clouds, both concepts were tested through seeding experiments.

Hailstorm seeding experiments conducted in Alberta have involved treating a feeder cloud and then documenting the effect of the treatment with observations made by the cloud physics research aircraft. Once a feeder cloud became too vigorous and too

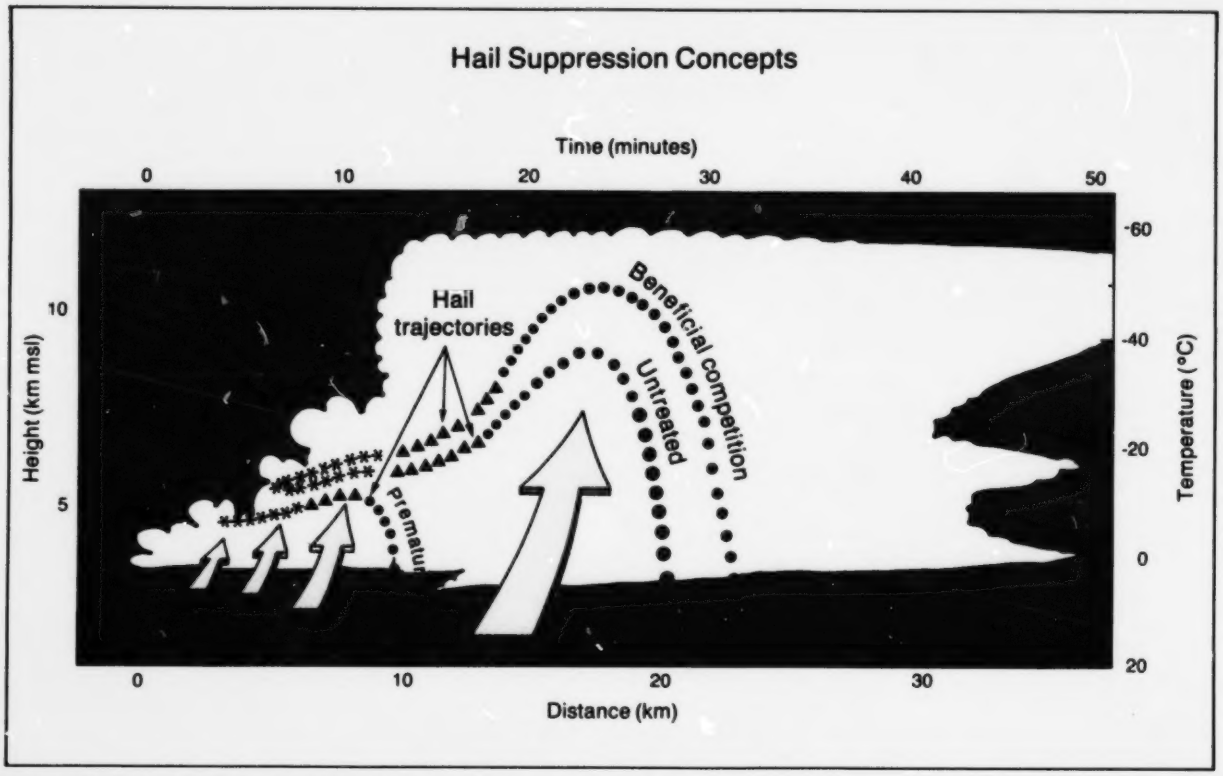

Figure 10. This illustrative slice through a typical hailstorm shows the expected paths of hailstones with and without seeding. After their beginning as embryos in the feeder cloud, the particles grow rapidly in the main updraft to fall as hailstones. Seeding the feeder clouds to introduce large numbers of ice crystals at the same time as natural ones are forming produces many artificial hail embryos that compete for the cloud's water supply. This competition limits the size of all embryos, resulting in smaller hailstones with a higher path through the storm. On this higher path (labelled beneficial competition), the stones grow slower and fall out of the storm as smaller hail. With some clouds, seeding the feeder cloud to cause ice crystals to form earlier allows hail embryos to precipitate out as rain before they reach the main updraft (premature rain out).

much a part of the mature storm to permit the research aircraft to penetrate it, precipitation particles from the feeder cloud could usually be identified and tracked by weather radar. In addition, storm chase vehicles collected hailstone samples in the precipitation area. During the experiments carried out in 1985, observations were also made using an armored aircraft (a T-28 from the South Dakota School of Mines and Technology), which was able to fly through the center of the storm.

The treatments used in the seeding experiments included a placebo (no seed), droppable silver iodide flares, or dry ice pellets. With the dry ice pellets, a low and a high rate were used, so that a total of four different treatments were used. The treatment was usually applied at about the −10°C level; when the scientist onboard the research aircraft thought that there was a possibility of success with the premature rain out concept, the treatment was applied at the −5°C level.

Test clouds were required to satisfy certain criteria to ensure that all treated feeder clouds were similar. Ideally four feeder clouds from one storm were treated as part of one experiment—each cloud receiving a different treatment—so that differences measured could be attributed to the treatment.

A completely successful series of seeding experiments (four treatments) is extremely difficult to achieve since identification of a suitable feeder cloud, treatment and subsequent observation of the cloud can take as much as an hour. A storm will often change dramatically or move out of the project area before an experiment is completed. In addition, the radar data, research aircraft data, weather observations and observations of rain and hail at the ground result in several kilometres of computer tape and millions of data values. Checks of data quality, extraction and analysis of relevant information, comparison of the various sources of information and interpretation of the results take months of effort for each case.

To date, six hailstorms have been analyzed. In four of these, a placebo as well as a seeding treatment were successfully applied. Data from six more successful hailstorm experiments and at least 10 additional partial experiments remain to be analyzed.

The seeding concepts can also be tested theoretically by using computer models to simulate atmospheric conditions. One such test was conducted with the assistance of the Institute of Atmospheric Sciences at the South Dakota School of Mines and Technology.

Experimental results

Hailstorm seeding experiments

Results from the seeding experiments indicate that the current understanding of how hailstorms function is

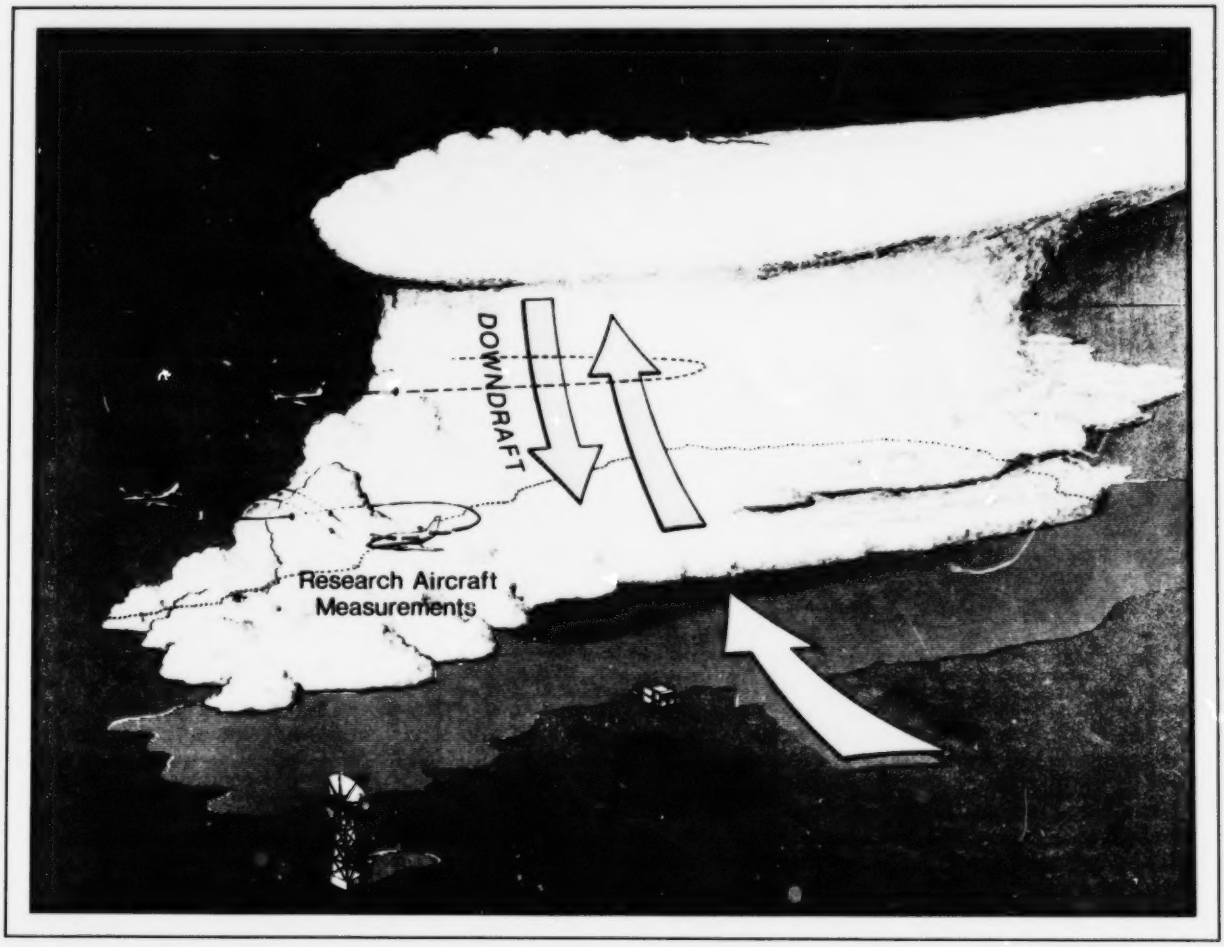

Figure 11. An artistic rendering of a hailstorm seeding experiment. If the research aircraft's first measurements determine that the feeder cloud meets requirements, the seeder aircraft, following, is instructed to release a seeding treatment. Subsequent penetrations by the research aircraft document the effects of the treatment. Cloud penetrations continue until hailstones are too large to permit further safe cloud measurements. Then the T-28 aircraft enters the main updraft region of the storm to continue measurements of the treated cloud. Following its treatment pass, the seeder aircraft retreats to a safe distance to photograph the storm. Chase vehicles intercept the storm to measure the hail and document the effects of the treatment. Weather radars record the storm's evolution and intensity of precipitation.

appropriate for Alberta and for the most part correct. Radar analysis of isolated storms indicates that 80 to 90 percent of storms that occur in Alberta are consistent with the model: storms have feeder clouds associated with them in which the precipitation process is initiated, and particles which form in the feeder clouds fall to the ground as hail.

An abundance of ice crystals was observed in all seeding experiments soon after seeding with either dry ice or silver iodide. The number of ice crystals in the seeded feeder clouds was very much greater than the number in unseeded clouds at comparable stages in the cloud life. These high numbers of ice crystals were intially observed in a very small part of the cloud, but with time they spread and grew—some of them becoming potential hail embryos within 10 minutes.

The number of potential hail embryos in the seeded feeder clouds was consistently about 10 times greater than the number in the unseeded clouds (beneficial competition concept). When seeded feeder clouds were sufficiently distant from the main storm, seeding encouraged the early formation of precipitable particles (premature rain out concept).

For safety reasons, the research aircraft cannot follow the treated feeder cloud once hail embryos have grown into centimetre-sized hailstones. Detailed analyses of the trajectories of radar reflectivity patterns (which are related to the particles growing within the feeder clouds) have led to the conclusion that such feeder clouds contribute particles which precipitate in the hailswath. Current radar analysis techniques are not sufficiently sensitive, however, to determine what effect additional hailstone embryos have upon the size and number of hailstones within the storm.

This problem was recognized after the third year of the program, and thus the armored aircraft of the South Dakota School of Mines and Technology was brought to Alberta in 1985. However, 1985 proved to be a year of low hailfall, and this aircraft successfully participated in only one hailstorm seeding experiment

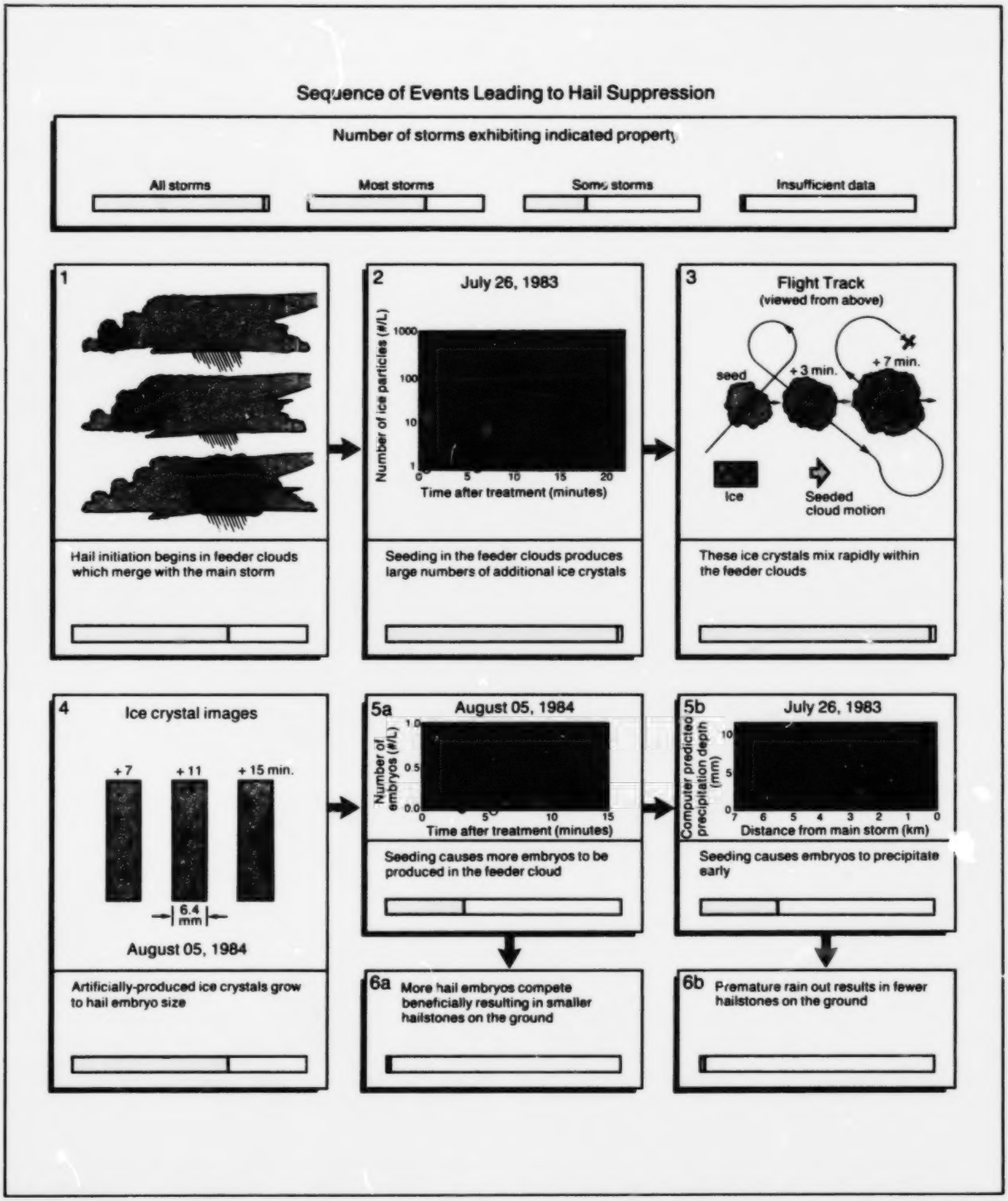

Figure 12. Sample results from testing the hail suppression concepts. Panel 1 illustrates the concept of hail formation. Panel 2 shows a comparison between the number of ice crystals in a seeded and unseeded feeder cloud as a function of time after treatment. Panel 3 indicates the spreading of ice crystals in a feeder cloud as determined from a sequence of aircraft passes through the cloud. Panel 4 shows the recorded images when ice particles intercept the laser beams onboard the research aircraft. Panel 5(a) (beneficial competition) illustrates the difference in numbers of hail embryos in seeded and unseeded feeder clouds. Panel 5(b) (premature rain out) shows the amount of computer-simulated precipitation from seeded and unseeded feeder clouds. Premature rain out is indicated in the seeded cloud. Panels 6(a) and 6(b) remain to be confirmed. The bars at the bottom of the panels indicate the degree to which that step of the suppression concept has been verified.

on July 11—an extremely severe storm. Analyses indicate that this storm was not sufficiently well seeded using current techniques. This was due in part to the fact that the feeder clouds for this severe storm grew right on the edge of the storm, allowing insufficient time for artificially produced embryos to prematurely rain out. In addition, there were exceptionally strong updrafts in this storm which required more seeding material than could be applied in the experiment. These very intense storms appear to constitute less than 20 percent of the damaging hailstorms that occur in central Alberta.

Observations of hail collected at the ground from one operationally seeded storm suggest that the number of hailstones on the ground was increased through cloud seeding. Not enough data were obtained to determine if the size of the hailstones was reduced to any significant degree.

Computer calculations

The Institute of Atmospheric Sciences at the South Dakota School of Mines and Technology used a computer model to simulate the seeding experiments that were carried out on a storm that occurred in Alberta on July 26, 1983. The calculations show that the feeder clouds were a source (although not the only one) of hailstone embryos; that seeding produced many ice crystals which spread through the cloud and grew with time; and that the seeded feeder cloud precipitated earlier than the unseeded feeder cloud. Furthermore, a temporary competition for the liquid water was seen. This suggests that seeding must be continuous, as it is in operational cloud seeding, to maintain this competition.

The computer simulations suggest that seeding one feeder cloud increased surface amounts of rain modestly (approximately seven percent) and decreased hail amounts somewhat (approximately nine percent). The computations verify that seeding resulted in the premature initiation of precipitation in this storm.

The results of these numerical tests cannot currently provide definitive answers regarding the effects of seeding because numerical models cannot yet simulate all the complexities of nature, but they do give indications of what seems reasonable to expect and what to look for in observations of the actual storms.

Economic assessment of hail suppression techniques

The experiments discussed in previous sections provide encouraging indications that cloud seeding can affect the amount of hail that falls to the ground, but the question of what economic benefit cloud seeding can provide can only be addressed in a properly designed statistical experiment.

One type of cost-benefit assessment involves the use of crop insurance data. A loss-to-risk ratio is often used to assess hail damage. This is the ratio of crop loss caused by the hailstorm to the risk or insured value of the crop, and is usually expressed as a percentage. Many evaluations of hail suppression programs have used the loss-to-risk ratio, usually with mixed results, except in the Soviet Union and France where significant reductions in hail are claimed.

Alberta farmers have purchased insurance against crop losses since the first settlers began farming operations in the latter half of the nineteenth century. The most consistent records in the province are those of the Alberta Hail and Crop Insurance Corporation and its predecessor, the Alberta Hail Insurance Board, spanning the period from 1938 to the present. These records represent the bulk of insurance policies purchased by farmers within the province.

Recent analyses of crop damage data from the Alberta Hail and Crop Insurance Corporation suggest a decrease in the loss-to-risk ratio of the order of 20 percent could be attributed to cloud seeding if no significant changes in weather patterns have occurred in central Alberta in the past 50 years and if no other factors have contributed to the observed decrease.

However, hail insurance data do not necessarily provide an accurate measurement of hailfall over an area because factors such as wind, crop type and growth stage determine how much damage will be caused by a given hailstorm. In addition, trends due to climate change, cloud seeding and changes in insurance practices are difficult to isolate. For this reason, a cost-benefit analysis of hail suppression should not rely primarily on insurance data.

In preparation for a future definitive cost-benefit analysis, some effort has been devoted to determining optimum measurements of hailfall. Results obtained to date suggest that time-resolved hailstone samples and some radar parameters provide measurements of hailfall that are accurate enough to produce definitive results from a statistical experiment of relatively short duration (five to ten years). Factors that influence hail, such as particular weather patterns and storm environments, have been identified and can be used in the future to separate effects due to changes in climate from those due to cloud seeding. Techniques have been developed to quantify the extent to which a storm is successfully seeded, so that an improper application of seeding material can be taken into account.

The Economic Services Division, Alberta Agriculture, has analyzed the effect of hail and drought on major crops in Alberta. In one analysis, the estimated average hail damage in 1985 dollars for the 1980 to 1985 period is 146 million annually. All analyses also show "that a loss recovery percentage of under 10 percent is sufficient to break even on hail suppression system costs". In particular, one analysis indicates that "benefits equivalent to 6.5 percent of premiums and administration costs are sufficient to pay for the total system cost". If secondary benefits and total crop value are considered, the loss recovery can decrease to less than three percent.

Summary and conclusions

The emphasis of the weather modification program over the past five years has been to better understand the hail formation process and the effect cloud seeding has upon it. A storm model was formulated which describes the current state of knowledge. This model has been shown to be appropriate for at least 80 percent of

the hailstorms that occur in Alberta. Seeding concepts have been tested with seeding experiments and with computer calculations.

Results from the six hailstorm seeding experiments indicate that cloud seeding can increase the number of potential hail embryos produced by the feeder clouds or, in some storms, can cause potential hail embryos to precipitate out of the feeder cloud prematurely. Because of limitations in measuring and observing facilities, it has not yet been demonstrated that more hail embryos lead to smaller hail on the ground, nor that premature rain out of embryos results in fewer hailstones on the ground.

Computer calculations for one hailstorm have confirmed that premature rain out from the feeder cloud occurred. The calculations suggest that this resulted in a moderate decrease in the amount of hail (approximately nine percent) and a moderate increase in the amount of rain (approximately seven percent).

Statistical analysis of crop damage data from the Alberta Hail and Crop Insurance Corporation suggests that a decrease in the loss-to-risk ratio of the order of 20 percent could be attributed to cloud seeding if changes in weather patterns and insurance practices have had no significant effect on this ratio.

Statistical analysis of hailstones from untreated storms and from one operationally seeded storm shows that cloud seeding increased the number of hailstones on the ground. However, not enough data were obtained to determine if the size of the hailstones decreased significantly.

Aside from these results on the feasibility of suppressing hail through cloud seeding, significant progress has been made in other areas. The time and location of storm development and the size of hail can be more accurately forecast. A foundation of knowledge has been built up whereby it is now possible to study the effect of cloud seeding on the storm environment and hence on the development of new clouds and storms. A technique has been devised to separate effects of the storm environment and seeding coverage from effects due to cloud seeding on hailfall and a method of quantifying seeding effectiveness has been developed.

These results give reason to be optimistic about the possibility of suppressing hail to some extent in the most common types of storms and of detecting and economically assessing the suppression effect. The potential benefit to the agricultural community of cloud seeding for hail suppression is great and the cost of seeding is small in comparison. Although the final step in the hail suppression process (cloud seeding to reduce hail damage) has not been validated, encouraging indications that cloud seeding can affect hailfall on the ground have been found. No evidence has been found that cloud seeding cannot succeed. Thus operational cloud seeding for hail suppression appears to be a positive tool for agriculture.

Rain

The potential of rainfall augmentation

Rainfall over much of southern Alberta is barely adequate in an average year, yet natural variations are such that the rain received in the growing season can be as much as 30 percent below normal once every five years. Even worse, much of this area can expect precipitation during July to be 60 percent below average once every five years.

Even when precipitation is averaged over five summers, large departures from the 30-year norm are frequently observed. Summers of the past decade have been characterized by below-average rainfall along the Bow River with above-average rainfall in the Drayton Valley area and the regions to the north and west of Edmonton. Southern Alberta has seen wide changes from very dry (as much as 40 percent below average in the late 1960s and early 1970s), to very wet (up to double the average rainfall in the mid-1970s) and back to dry again in the early 1980s. Departures of 30 or 40 percent above or below normal are common. During 1984 and 1985, the rainfall was very much below normal.

Weather modification is one means of increasing rainfall. Cloud seeding has been seen as a means of increasing the water supply in many areas of the world. Particularly well known is a project in Israel which used silver iodide to seed winter convective clouds. A statistical analysis showed that seasonal precipitation was increased by 15 percent.

In Canada, the Atmospheric Environment Service carried out seeding experiments on cumulus clouds in Yellowknife and Thunder Bay. Clouds in both areas showed increases in ice concentration with seeding and, in Yellowknife, 40 percent of the clouds produced rain.

Cumulus seeding experiments in Alberta in 1978 and 1979 produced dramatic radar evidence of rain augmentation through cloud seeding. These experiments and the encouraging results reported from elsewhere, led to the initiation of a series of rain seeding experiments in Alberta.

Rainfall augmentation concepts

Modern rain augmentation projects have been based on the belief that convective clouds are inefficient rain producers because of a lack of natural ice nuclei. It is believed that seeding convective clouds with an ice nucleating material will convert more of the cloud water to ice. Ice particles will grow faster than water droplets and so will become heavy enough to fall out of the cloud faster than water droplets. The ice particles melt as they fall to the ground and arrive as rain.

Testing the rainfall augmentation concept through cumulus cloud seeding experiments has been a secondary objective of the weather modification program. These experiments were designed to document the processes of rain development in natural and seeded cumulus clouds, to determine the range of condi-

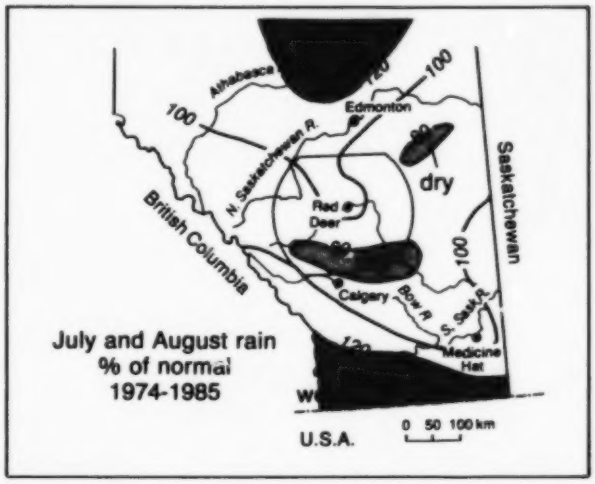

Figure 13. Rainfall in Alberta varies considerably from region to region and from one period to another. This map shows the 1974 to 1985 summer rainfall (July + August) as a departure from the 30-year normal from 1941 to 1970. The shaded areas show regions with more than 20% departure from normal. No clear pattern consistent with the cloud seeding areas is evident.

tions under which clouds can be made to rain through cloud seeding, and to determine the most effective treatment.

Rainfall in Alberta is produced by widespread weather systems, thunderstorms and cumulus shower clouds. This rain is usually melted snow or graupel that grew in the cloud from tiny ice crystals. Since cumulus clouds with tops warmer than −15°C do not tend to rain naturally, such clouds were chosen for experimentation to simplify evaluation of the effect of seeding.

Seeding experiments were carried out whenever isolated cumulus clouds or cumulus clouds embedded in a stratus cloud deck occurred in the project area and equipment was not required for hailstorm seeding. The experiments involved choosing a test cloud according to characteristics measured by the research aircraft. An appropriate treatment of either silver iodide or dry ice pellets, or a placebo (no treatment), according to a random sequence, was applied to the test cloud. The treatment effects were observed by repeated flight through the treated cloud by the research aircraft. Radar observations were also made to monitor precipitation development in the cloud.

Results of the seeding experiments

During the period 1982 to 1985, 98 experiment clouds were selected. Ten clouds had to be rejected during analysis due to missing information. Out of the 88 clouds analyzed, 57 had been treated with a seeding agent and 31 were treated with a placebo (control clouds).

Observations with the research aircraft show that the class of cumulus clouds selected for the experiments do not naturally produce high concentrations of ice crystals. Seeding these clouds with either silver iodide or dry ice is effective in producing high ice crystal concentrations and these ice crystals spread through the cloud and grow with time.

None of the test clouds that lasted less than 20 minutes developed precipitation. Twelve of the control clouds lasted for 20 minutes or longer, but none of these developed precipitation. Thirty-six seeded test clouds lasted for 20 minutes or longer after the seeding agent was applied and developed precipitation (i.e. 63 percent of the seeded clouds were observed to have rain fall out of the cloud at cloud base). Twenty of the 36 clouds were suitably located to determine if rain fell to the ground. It is estimated that 35 percent of the seeded clouds that lasted for 20 minutes or longer produced rain on the ground or 22 percent of all seeded clouds produced rain on the ground. All the test clouds that produced rain on the ground were seeded with silver iodide.

Rainfall estimates calculated from the radar data indicate that the test clouds produced up to 16 000 cubic metres of rainwater when seeded and covered areas up to 140 square kilometers which averages to 0.1 mm of rain. In one case, 0.9 mm of rain was measured at the ground.

Cloud climatology studies

To enable estimates of the potential impact of the results of the seeding experiments on regional rainfall, a cloud frequency study was undertaken. This study showed that on average, during the summer months, 7 to 11 percent of the sky in southern Alberta is covered with the type of clouds investigated in the seeding experiments. The study also indicated that clouds of the type used in the experiments are just as prevalent during a drought as they are during a non-drought period. The climatology studies suggest that an additional 10 mm of rain could be realized from seeding isolated cumulus clouds during the summer. With larger cloud systems this could be increased even more.

Alternative seeding techniques

Cloud-base seeding

An exploratory study was undertaken during the 1985 field season to test the cloud-base seeding technique for accuracy of delivery. Results from four experiments showed that silver iodide delivered at cloud base was transported into the cloud. Distinct seeding effects were observed similar to those seen with cloud-top seeding. Therefore, although the timing may be more difficult to control, it seems that seeding at cloud base is an alternative to seeding within, or above, a cloud near its top.

Ground-based seeding

An alternate method to both cloud-top and cloud-base seeding with aircraft is seeding from the ground using some form of silver iodide generator. Such devices have the advantage of simplicity, ease of access, no aircraft operating costs and manual operation.

A project to evaluate the efficiency of seeding summer clouds using ground-based silver iodide generators was also conducted as part of the weather modification program. This technique has been used by I.P. Krick and Associates in Alberta and elsewhere

for more than 30 years. The test system involved a network of the coke-fueled and arc generators installed at 60 to 70 sites in southern Alberta during the summers 1981 through 1985. The coke generators burn pellets of coke that have been soaked in a solution which contains silver iodide, while the arc generators burn pure silver iodide by means of an electric arc. The operational objective was to increase rainfall in a 15 000 square-kilometre target area south of Calgary.

Mapping and plume-tracking flights conducted in conjunction with the *I.P. Krick* ground-generator operations in southern Alberta showed that the

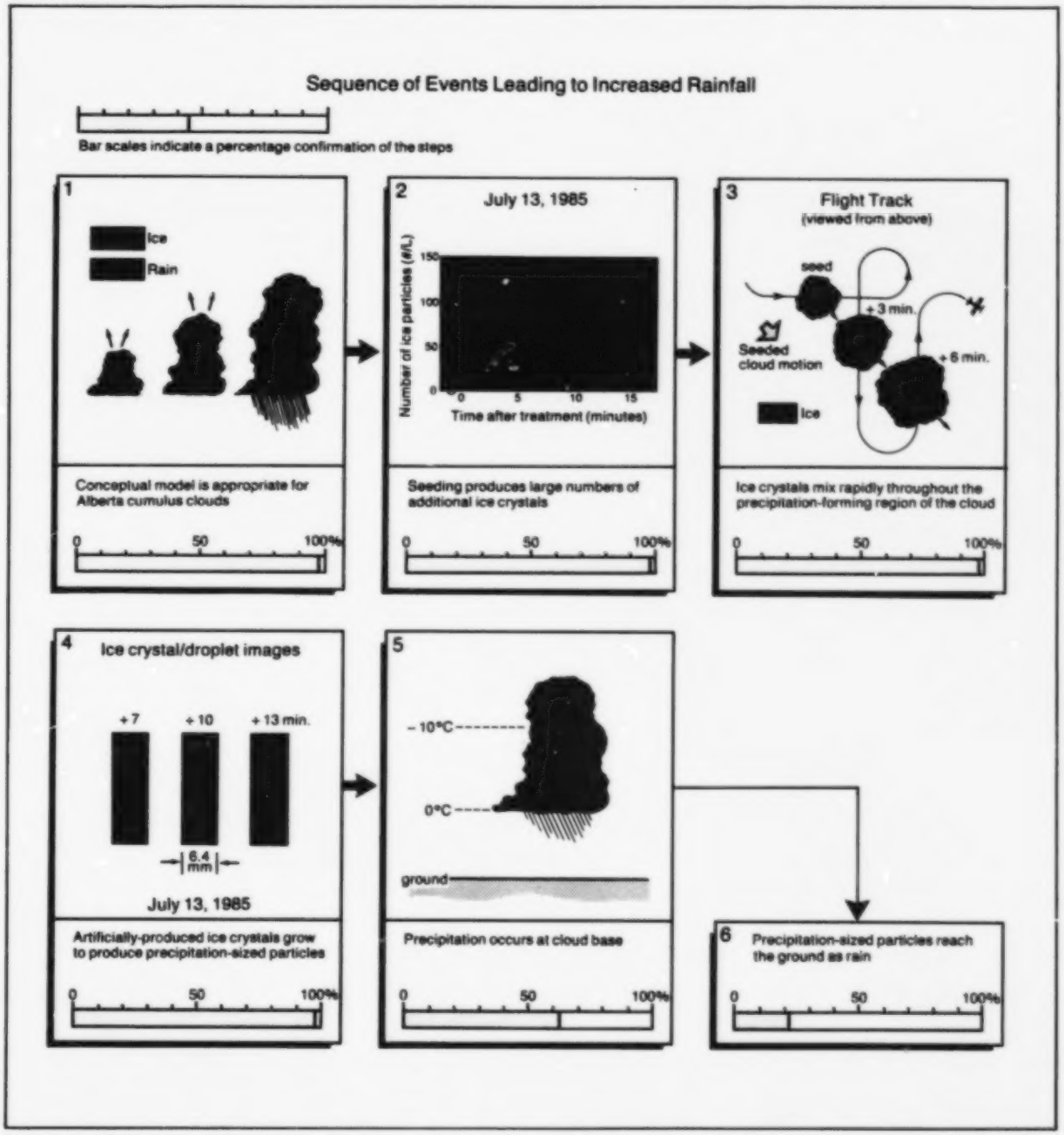

Figure 14. Sample results from rainmaking experiments. The panels indicate steps in the rain augmentation concept and the bars show the degree to which each step has been verified. Panel 1 illustrates the concept of rain formation in an Alberta cumulus cloud. Ice crystals form on ice nuclei in the cloud's updraft and grow as the cloud provides moisture. When the updraft dies, the particles fall, and melt to form rain. Panel 2 shows the number of ice crystals in a seeded and a natural cloud as a function of time. Panel 3 indicates the spreading of ice crystals in the cloud. Panel 4 shows the images recorded when ice particles and water drops intercept the laser beams onboard the research aircraft during several passes after seeding. Panel 5 illustrates that for the clouds which last 20 minutes or longer after seeding (63%), ice particles grew large enough to fall out of the cloud. Panel 6 shows that 22% of the seeded clouds produced rain on the ground.

generators typically produced narrow plumes a few hundred metres wide occupying a few percent of the target volume. Occasionally, plumes were encountered near cloud base.

Laboratory tests of the generators by Colorado State University showed they did produce effective ice forming nuclei albeit at lower rates than other systems.

An independent statistical evaluation of the effect of ground-generator cloud seeding in southern Alberta was carried out by the University of Alberta. This study concluded from three different analyses that no evidence of a change in rainfall greater than 12 percent could be found.

Summary and conclusions

The cumulus seeding experiments have shown conclusively that some cumulus clouds that would not rain naturally can be made to rain by seeding with an ice nucleating material. Of the clouds seeded in the course of these experiments, 22 percent produced rain on the ground and rainfall was observed at cloud base in 63 percent. While half the test clouds were treated with dry ice, all of the clouds that produced rain on the ground were seeded with silver iodide.

Seeding at cloud base with aircraft seems to be a viable alternative to seeding at cloud top. No conclusions can yet be drawn about the effectiveness of seeding from the ground with ground-based generators.

The experiments conducted to date have dealt with a very specific type of cloud which is equally prevalent in times of drought and of normal rainfall.

These results indicate that cloud seeding for rain augmentation should be considered as a tool for water management. However, before the economic potential of this tool can be assessed, further experiments are required to optimize the seeding techniques and to assess the potential of increasing rain from other types of summer clouds. Before appropriate clouds can be seeded routinely, it must be determined if there are any kinds of clouds for which seeding would decrease rainfall. If such clouds exist, the seeding technique must be able to exclude them in routine seeding operations.

Finally, a properly designed statistical experiment will be required to determine economic benefits. Such an experiment should include considerations of downwind effects, that is, the possibility that cloud seeding in one area robs some area downwind of its rain.

Snow

Potential of snowpack augmentation

Inadequate rainfall during the growing season can be alleviated in some areas through irrigation. Much of the water currently being used to irrigate crops in southern Alberta comes from spring runoff, and it is estimated that a 10 percent increase in the average cumulative mountain snowpack would result in 250 000 acre-feet of increased runoff in the Oldman River basin alone, adding greatly to irrigation and other water supplies. Municipalities would also benefit from additional snowpack.

Research and development into cloud seeding for snowpack augmentation is underway in the western United States to help alleviate potential water shortages. Projects are currently being conducted in California, Colorado, Montana, Nevada and Utah by various universities, state and federal agencies, including the U.S. Department of the Interior and the National Oceanic and Atmospheric Administration (NOAA). Cloud seeding in the mountains has been identified recently by the United States Secretary of the Interior as "the most cost effective and promising means of meeting the water needs of the Colorado River basin."

U.S. results indicate that cloud seeding may increase the mountain snowpack by about 15 percent. In Colorado, it has been estimated that such increases could augment streamflows by 10 percent.

Snow augmentation concept

Cloud seeding for snow augmentation is also based upon the fact that the atmosphere is not always naturally "efficient" in producing precipitation. In a moderate westerly airflow over a mountain ridge, with clouds one km deep and extending one hundred km along the mountains, about 5000 cubic metres (one million gallons) of water, pass over the ridge each minute. Because of a scarcity of ice nucleating particles, supercooled water droplets in these clouds often do not freeze even at temperatures much colder than zero. In the absence of ice nuclei, the cloud droplets evaporate in the descending air on the leeward side of the mountain barrier.

In a weather modification program, ice nucleating agents (either silver iodide or dry ice pellets) are delivered to the cloud to initiate snow crystal growth. The seeding principles for converting cloud water to snow are very similar to those for rain augmentation.

Alberta investigations

A limited investigation of the feasibility of increasing snowfall over the southern part of the Alberta Rocky Mountains was carried out during the past five years.

A preliminary assessment of the snow climate and clouds of the southern Canadian Rockies was recently completed which investigated the snow climatology of the region and measured the properties of winter clouds over the mountains. The snow climatology showed there are different snowfall patterns on each side of the continental divide. The spring contribution to the total snowpack was noted. The climate studies indicated that meteorological conditions within the region were appropriate for cloud seeding technology.

Measurements by the research aircraft during four two-week field programs from 1982 to 1984 showed evidence of liquid water in the clouds and an increase

in liquid water near barrier peaks. Estimates for three selected cases indicated less than one percent to 16 percent of the moisture was converted to snow. These results suggest that the precipitation process could be made more efficient if artificial ice nuclei were added.

Summary and conclusions

Limited observations from snow clouds over the Rocky Mountains in southern Alberta show that potential exists to increase mountain snowpack. Therefore, a project called SNOWATER has been proposed to adapt snow augmentation technology for use in Alberta.

Technological benefits of the program

Atmospheric research to study weather modification requires a broad base of expertise in such disciplines as meteorology, statistics, computing and electronics as well as a broad range of supporting technologies. The Alberta Research Council has developed a first-class team of experts and new technologies that can be applied to other types of research and problem solving with a positive impact on the province.

A major component of the program was the cloud physics research aircraft developed jointly with INTERA Technologies through funding from Alberta Agriculture and the Alberta Research Council. This aircraft's instrumentation can measure many cloud-related and atmospheric parameters such as temperature, humidity, pressure, cloud droplets, raindrops and winds. The data is stored, processed and displayed in the aircraft with the aid of a computer data acquisition system.

The research methodology and cloud seeding technology has assisted INTERA in the international marketplace. They are actively marketing the research aircraft facility as well as the weather modification technology they have acquired by participating in the Alberta project. Other countries have expressed an interest in involving INTERA Technologies and the research aircraft in their weather modification programs to the extent they now have a three-year, $10 million weather modification contract with the Greek government. This successful marketing of Alberta expertise and technology would not have been possible without the weather modification program in Alberta.

The meteorological expertise associated with the weather modification program has been contracted to Alberta Environment to support studies of air quality in Fort McMurray and Calgary. The research in Fort McMurray involved using the research aircraft to track effluent plumes from oil sands processing plants.

The Alberta Research Council is currently finalizing arrangements with the University of Dayton, Ohio, to supply aircraft data collected during the program to be used in updating icing standards for commercial aircraft.

The computing expertise used in weather modification research has been very useful in applying many of the technologies to unrelated projects. All aspects of the research and operations now rely on computing to store and analyze data from the research aircraft, the weather radar systems, the weather information from the Atmospheric Environment Service and even the data obtained from telephone surveys of farmers. Some of the programs used to support the graphic representation of the data will soon be used by Alberta industry. Other programs used to access and store the meteorological data from the Atmospheric Environment Service have been used by Syncrude in their environmental work.

Statistical expertise used in weather modification evaluations has also been applied to crop yield modelling for Alberta Energy and Natural Resources and in oil production studies for AOSTRA.

Research on hailstorms has improved the ability to forecast convective weather. A computer program that produces weather forecasts in a manner similar to the human meteorologist (using artificial intelligence techniques) has been developed and may soon be in the private sector. In addition to aiding weather modification research and cloud seeding operations, improved forecasts of hailstorms provide more accurate and timely warnings for the public so that precautions can be taken such as diverting flights, putting aircraft and vehicles under protective covering, drawing blinds to protect against broken glass and seeking cover from large hail which can inflict severe injury.

Weather radar is needed to detect and track storms for weather modification research. Radar can also be used to estimate rainfall over broad areas, which is useful in predicting stream flow. A facility has been added to the weather radar system in Red Deer that has the capability of transmitting measurements to the Alberta River Forecast Centre in Edmonton as rainfall occurs. In addition, computing technology has been adapted so that radar information from the Atmospheric Environment Service's weather radars in Vulcan and Stony Plain can be collected and transmitted to the River Forecast Centre.

The radar data collected as part of the weather modification program have been analyzed for Alberta Disaster Services to assist in assessment of severe weather events and applied to the development of forecasts of damaging lightning for the Canadian Electrical Association. Radar data are also being used by Alberta Government Telephones to study signal fading during heavy rainfall.

These contracts indicate that other Alberta agencies are developing a reliance on the weather radar system that supports weather modification research.

Recommendations

Hail

1. Major progress has been made in understanding the hailstorm and the formation of hail, but several basic questions remain:
   - how does seeding affect the energy and organization of a storm,
   - are feeder clouds the prime source of hail embryos,
   - can the available liquid water in the feeder clouds be depleted by cloud seeding,
   - what happens to the embryos once in the main storm, and
   - can the inflow be adequately seeded?

   It is recommended that a hail suppression research program be conducted to address these important issues. In particular, seeding experiments should be conducted in which all (or many) of the feeder clouds existing at any given time are treated in anticipation that such action would result in a radar-detectable effect on the main storm. Also, research efforts should be directed to improving application of the special capabilities of the Alberta Research Council's radar, to understanding the role of the storm environment, to observing the inflow region of storms, and to applying three-dimensional computer models of hailstorms.
2. **It is recommended that support be given to hosting and funding Alberta's participation in an international project called Hailswath II.** This project would see participants from the United States and Europe gather in Alberta in 1988, along with their sophisticated equipment, to carry out an intensive study of the hailstorm. This would mean that additional weather radars, research aircraft and other types of observational systems would be directed toward the understanding of Alberta hailstorms. Scientists from the participating countries would then analyze the data to answer questions about Alberta storms.
3. Computer calculations to date clearly suggest that the outcome of cloud seeding depends upon the seeding material used, the amount delivered and the delivery method. In order to optimize cloud seeding, it may be necessary to tailor the seeding technique to the specific storm to be treated. In fact, the very intense storms that do not presently appear to respond to current seeding techniques, may be treatable in some quite different fashion. **It is recommended that investigations of and experimentation with different ways of seeding with aircraft and from the ground be carried out.** It is felt that the efficiency of seeding delivery can be improved, enhancing the possibility of substantial economic benefits from hail suppression.
4. Weather modification to suppress hail has a very high potential economic benefit to the province. There is increased optimism about weather modification because of the research successes of the last five years. **It is recommended that an operational cloud seeding experiment be established. The goal of this program would be to evaluate the costs and benefits of operational cloud seeding.** To provide a comprehensive statistical evaluation, this program should be carried out over a single area as a 50/50 randomized test. With current knowledge and techniques, a conclusive evaluation would take five to 10 years. Once a decision is made on the type of confirmatory experiment that will be permitted a comprehensive design would take about one year.
5. **It is recommended that any operational cloud seeding should be carried out by the private sector.** However, a strong link should be maintained between the research and operational components of any future weather modification program. This link should include the sharing of resources to make the program as cost-effective as possible.
6. As part of a definitive cost-benefit assessment of cloud seeding for hail suppression, accurate measurements of hailfall are required. **It is recommended that time-resolved hail observations at the ground be emphasized, in any future program,** since this type of observation promises to be an effective evaluation tool.
7. Predicting the amount of hail produced by a storm would enhance the ability to detect the effects of cloud seeding. This requires a good understanding of the interactions of the storm with its environment. **It is recommended that studies of the storm environment and storm forecasts continue.** The continuation of such studies are important to determine if seeding will produce any adverse effects some distance away; whether seeding will alter the region's climate; whether "early seeding" can suppress storm development and produce widespread showers instead of an intense hailstorm.

Rain

1. **It is recommended that seeding experiments to increase the rainfall from summer clouds in central and southern Alberta be continued with a greater emphasis on larger clouds and on optimizing seeding techniques.** Larger clouds will entail investigating the possibility of cloud seeding increasing the rainfall from clouds that rain naturally.
2. In preparation for an area-wide experiment, **it is recommended that the problem of overseeding some clouds be investigated.** The maximum as well as the minimum amount of seeding material that can produce a beneficial effect on rainfall from a particular cloud must be known if all clouds in an area are to be seeded with an average rate.
3. **It is recommended that a statistical experiment be designed to assess the cost-benefit ratio of operational cloud seeding for rainfall augmentation.** Elements of the design would include the specific measurements of rainfall and other factors

that are to be used, the seeding effectiveness and how it is to be quantified, bias in the selection of seeding events and how it is to be handled.

Snow

It is recommended that snowfall augmentation research be initiated and that a project called SNOWATER, proposed as a mechanism for the adaptation of snowfall augmentation technology for Alberta, should be funded.

Technology development

It is recommended that the application of expertise and technology developed for weather modification research to other problems be continued and that the transfer of appropriate technology to the private sector also be continued.

Conclusion

The highlight of the recent program has been the success of the rain augmentation project. This aspect of the weather modification technology has been solidly demonstrated on a limited scale. The hail problem is the most complex and difficult to solve, but substantial progress has been made and hail suppression appears to be feasible at least for some types of storms. The potential to increase snowfall through cloud seeding has been demonstrated and the technology is promising. The potential economic gains from cloud seeding are substantial. Results of the last five-year program lead to optimism about the use of cloud seeding to benefit the province's economy and technological capabilities. It is recommended that weather modification receive continued support.